Testing Thermodynamic Models of Dark Matter Halos

Eric I. Barnes, Department of Physics

1. Introduction & Significance

An overarching goal of astrophysics is to understand the structure of the cosmos and the phenomena that guide its evolution. Looking into the night sky, it is natural to assume that only visible matter influences the evolution of the universe and the galaxies within it. In 1933, astronomer Fritz Zwicky directed his telescope to observe the motions of galaxies within the Coma Cluster. His observations led him to infer that the relative velocities of the galaxies comprising the cluster were far too great for them to be held together by the gravitational attraction of the visible matter alone (Zwicky 1937). However, the measurements involved significant uncertainties, and few scientists seriously considered the idea of this "dark matter" that can only interact gravitationally. Decades later, Vera Rubin and Kent Ford found evidence that the motions of spiral galaxies contradicted Newtonian predictions (Rubin & Ford 1970). Specifically, one would predict that stars and gas orbiting far from a galaxy's center would have smaller circular speeds when compared to stars and gas orbiting closer to the center. However, Rubin and Ford found outlying stars and gas to travel at approximately the same speeds as those orbiting much nearer the centers of galaxies. Since this pioneering work, numerous studies of spiral galaxy rotation curves have found similar stellar/gas orbital behavior (e.g., de Blok et al. 2001; Barnes, Sellwood, & Kosowsky 2004). Like Zwicky's work with galaxy clusters, the motions of stars and gas in spiral galaxies suggests that there must be an unseen mass component to galaxies. In the case of spiral galaxies, a roughly spherical halo of mass surrounding a galaxy would allow an explanation of the observed flat rotation curves — even though the visible mass is nearly all accounted for near the outer edge of a spiral, the halo mass continues to rise and provides the extra gravitational pull to maintain the nearly constant circular speeds. The extent of dark matter systems suggests that they behave collisionlessly, where two-body encounters are insignificant. In other words, when gaseous and stellar components of proto-galaxies begin to collapse and radiate energy away, the underlying dark matter halo maintains its overall size.

In the latter half of the twentieth century work like that of Zwicky and Rubin begged the question, how can we be sure dark matter exists? In addition to dynamical studies, like those above, gravitational lensing techniques have since been developed to measure the amount of visible and dark matter present within galaxies and galaxy clusters (e.g., Clowe et al. 2006). As a consequence of general relativity, any object within the universe that possess mass intrinsically warps spacetime around it according to how massive it is; akin to a marble sitting on and bending a rubber sheet. The greater the mass of an object, the higher the degree of warping. Remarkably, any matter and energy that pass through these regions of warped spacetime experience a corresponding deflection. Gravitational lensing techniques exploit this phenomenon to estimate the mass of a system based on how sharply distant light is bent around the system.

Independent of the observational technique, the most useful quantification of the amount of dark matter present in a system is the mass-to-light ratio. Assuming all visible matter emits electromagnetic radiation and all dark matter does not interact electromagnetically, the mass-to-light ratio will provide a measure of how much mass is present in a galaxy relative to what is seen. It has been shown that within the Sun's Galactic orbit there are roughly ninety billion solar masses of matter (Faber & Gallagher 1979). Incredibly, there are only approximately fifteen billion solar luminosities within the same radius. In other words, within our Galactic radius there are roughly six solar masses per solar luminosity. Further analysis of outer Galaxy dynamics suggest that the mass-to-light ratio could reach values closer to 100 solar masses per solar luminosity (Binney & Tremaine 1987). Similar measurements have been made in galaxies across the cosmos, and in each such measurement, the data suggests there is more mass and less light at greater distances from a galactic center. Based on the inferred mass-to-light ratio in our neighborhood of the Galaxy, we expect a non-negligible density for dark matter within our solar system. Several laboratories, such as the University of Minnesota's Soudan mine facility, have been established to detect possible candidate dark matter particles. The Soudan mine leads the Cryogenic Dark Matter Search (CDMS), which seeks to isolate byproducts of dark matter particle collisions in the early universe (Ahmed et al. 2009). Unfortunately, since the inception of the dark matter hypothesis no acceptable candidate particle or object has been discovered.

A common alternative to observing dark matter is modeling dark matter and its influences on baryonic matter with computer simulations. In this approach, one aims to use comparisons between numerical predictions and observations to infer properties of dark matter. Over the past several decades, many groups have created models of dark matter halos with varying levels of sophistication (e.g., Navarro, Frenk, & White 1996; Moore et al. 1999). Taking advantage of ever-increasing levels of computing power, simulations with higher and higher resolutions (number of particles per halo) are constantly being performed. Our goal is not to attempt to replicate these state-of-the-art simulations, but rather to use more modest simulations to investigate some basic questions. As further clarification, the systems that we simulate are not direct analogues of putative dark matter halos, but they do share the fundamental physical conditions of self-gravitation and collisionless evolution. Our simulations are similar to those that have shown evidence of "universal" halo behaviors such as radial density profiles (e.g., Navarro, Frenk, & White 1997; Navarro et al. 2004). Power-law radial distributions of the quantity formed by dividing density by the cube of the velocity dispersion $\rho(r)/\sigma(r)^3$ (which has dimensions of a phase-space density, Taylor & Navarro 2001), have also led some to suggest that a more basic physical mechanism may underlie the formation of these self-gravitating equilibria.

The simulations my research group and I have performed, and are proposing to perform, create data sets of particle positions and velocities at equally spaced times during an evolution of a system. Such an approach is referred to as an N-body simulation, referring to the (usually) large number of interacting particles involved. Each simulated system is prescribed by a set of initial particle positions and velocities which have then been allowed to evolve. These initial conditions provide discrimination between the simulations. The industry-standard GADGET code (Springel 2005) has been used to advance particles in time according to calculated self-gravitating forces between the particles. GADGET utilizes softened particle-particle interaction forces to approximate collisionless behavior. Although the GADGET code is capable of including gas dynamics and Hubble expansion, we have elected not to include these features in our simulations. Although cosmological simulations involving these processes often result in "realistic galaxies" (e.g., Governato et al. 2010), they do not necessarily provide direct insight to the physical processes governing dark matter systems. The significance of the proposed work is that it will test specific physics against the results of simulations.

2. Objectives

2.1. Institutional Goals

This work will support my efforts to involve undergraduate physics majors in research. I anticipate this to be a true team effort between myself and students in my research group. This work will provide projects to students doing research for credit (PHY 498) and will hopefully lead to a future Dean's Distinguished Fellowship or Wisconsin Space Grant Consortium proposal submission.

2.2. Science Goals

To focus more on the physics involved in our N-body simulations, we will extend our investigation of how well models based on thermodynamic considerations describe the results of simulations. We will compare simulations to several common empirical fitting functions. Both the empirical and physically-motivated models will be fit to the simulated density and velocity distributions, after they have attained a steady-state. The suitability of each model will be judged using the reduced χ^2 statistic for quantifying differences between models and data. We will also extend the model/data comparison to include density and velocity dispersion profiles, a step often neglected in these kinds of studies (e.g., Lithwick & Dalal 2011).

For the proposed work, we will examine three physically-motivated models of self-gravitating collisionless systems. Non-extensive, Maxwell-Boltzmann, and Lynden-Bell models are based on thermodynamic approaches to understanding the equilibrium attained by our simulations. Non-extensive models arise from the idea that the usual rules of thermodynamics change when dealing with a self-gravitating system (Tsallis 1988; Plastino & Plastino 1993). The PI and his collaborator have derived the Maxwell-Boltzmann and Lynden-Bell models in previous work done at UW-L (Barnes & Williams 2012). These thermodynamic models are appealing because they a) ignore complicated microscopic (particle-by-particle) dynamics of the situation and instead focus on collective quantities, like entropy, and b) rely on only one or two adjustable parameters. This work will allow us to determine the applicability of these kinds of models to simple systems. As a result, we will gain insight regarding the physics involved in the formation of dark matter halos, and by extension, the galaxies that inhabit them.

3. Methods

As mentioned earlier, we have created and analyzed computational simulations of the evolution of numerous systems, each containing $N = 10^5$ particles. We want to create a more targeted set of GADGET simulations with $N = 10^6$ particles that will allow us to discriminate any numerical effects that may be present. We also aim to create additional $N = 10^5$ simulations using software that is different from the aforementioned GADGET to infer any "code-based" biases. This NBODY-6 code (Nitadori & Aarseth 2012) utilizes a Graphics Processing Unit to directly calculate gravitational forces between particles very efficiently, in contrast to GADGET which utilizes approximate methods. Thanks to past funding from the College of Science and Health, the PI has access to computers with sufficient hardware to run such simulations on the timescale of a month. Previous student research projects have built the numerical infrastructure needed to create and analyze the simulations.

3.1. Initial Conditions

When utilizing N-body simulations, there are numerous initial conditions that must be considered. For example, the initial position, the initial kinetic and potential energy, and the initial orientations of the velocity vectors of all particles must be defined. Moreover, the overall density distribution and the number of particles within the simulated halo must also be accounted for. Following the lead of van Albada (1982), we define two distinct initial particle position prescriptions for all simulated systems – single and clumpy setups. In a single setup, all particles are distributed throughout a single spherical boundary of a simulated system. Consequently, all particles in a single setup orbit about the center of mass of the system. On the other hand, particles in a clumpy system exist in a large number of smaller spherical subsystems. One can visualize a clumpy system like grapes in a spherical bunch, except clumps are allowed to overlap one another. Clump sizes (radii and masses) are randomly chosen from power-law distribution functions. For masses, this amounts to adopting a Salpeter initial mass function (Salpeter 1955) with an exponent of -2/3 to keep the number of clumps finite. We have not done extensive investigations of the impact of this exponent. In each type of setup, the specific particle locations are determined based on an assumed initial density profile. Our simulations assume initial density profiles that are either cuspy, $\rho \propto 1/r$, or Gaussian, $\rho \propto \exp\left(-r^2\right)$. Given an initial profile choice, particle locations are selected to reproduce the profile using a simple rejection method. For single systems, each particle position is specified. For clumpy setups, clump centers-of-mass are distributed according to the chosen profile, and each clump has a uniform distribution of particles within it.

With particle positions specified, the gravitational potential energy is calculated. This energy scale provides the basis for assigning particle velocities. The virial theorem provides a relation between a system's kinetic energy T, potential energy W, and second time derivative of its moment of inertia. For a steady-state system, $2T - |W| = 0$. We define the initial virial ratio as,

$$Q_0 = \frac{2T}{|W|}, \tag{1}$$

so that $Q_0 = 1$ indicates a system in virial equilibrium initially. We limit our investigations to systems in which $Q_0 \leq 1$, as $Q_0 > 1$ corresponds to an unbound system where evolution would entail mass loss. In general, systems with lower virial ratios tend to undergo early, violent collapses due to the dominance of potential energy, while systems with higher virial ratios tend to experience only mild density variations as they approach mechanical equilibrium.

All particles are given the same initial speed necessary to produce the kinetic energy. Particle velocities are assigned with random orientations, producing initially isotropic systems. In single systems, the velocity assignment is straightforward. However, assigning only one set of velocity vectors to a clumpy system is insufficient, as the particles can move relative to the system center-of-mass as well as the clump center-of-mass. As such, we define a temperature fraction T_f to distinguish the possible velocity arrangements. Systems in which particles initially move with the center-of-mass of their parent clump are designated $T_f = 1$. We refer to these conditions as “cold”, indicating a relative lack of random motion. Conversely, systems with particles that move entirely randomly with respect to the halo center of mass are designated $T_f = 0$. We refer to these systems as “hot”, reflecting the fact that the clumpy structure degrades quickly due to random motions. Systems where particles move with respect to both the centers-of-mass of the halo and their respective clump are “cool” and are designated $T_f = 0.5$.

3.2. Evolutions

For the simulations proposed, $N = 10^{5-6}$ particles will be used to define systems. In an effort to maintain connection to two commonly assumed properties of dark matter halos (classical dynamics and collisionless evolution), simulations discussed here include only Newtonian gravitational interaction between particles. We do not consider self-annihilation or other interaction terms.

Once a simulated halo has been prescribed with a set of initial conditions, it will be evolved using two publicly-available codes, GADGET and NBODY-6. Each code produces snapshots of the system at specified intervals, providing access to particle positions and velocities. Given a snapshot, we calculate radial profiles of density, velocity dispersion, and velocity anisotropy. To accomplish this, we first assign particles to concentric spherical shells. Each shell contains the 1% of particles closest to the system center-of-mass that have not already been assigned to an interior shell. Using the shell boundaries, the average density is then calculated. Splitting each shell into three sub-shells and determining their densities allows us to estimate uncertainties as the range of sub-shell densities. Radial, polar, and azimuthal velocity statistics (averages and root-mean-square values) are also calculated per shell. Uncertainties for these quantities are estimated similarly to those for density.

3.3. Fitting Models

We fit the empirical and thermodynamic models to density and velocity dispersion profiles derived from simulations after the simulations have settled to mechanical equilibrium. Mechanical equilibrium is verified by guaranteeing that the virial ratio of the system has reached a value of one and that the average radial velocity is zero throughout the system. We use the reduced χ^2 statistic as the figure of merit for our fits,

$$\chi^2 = \frac{1}{N_{\rm data}} \sum_{i=1}^{N_{\rm data}} \frac{(M_i - D_i)^2}{\Delta_i^2}. \tag{2}$$

The first term “normalizes” the value of χ^2 according to the number of data points, $N_{\rm data}$. A data point value is denoted D_i, the corresponding model value is M_i, and Δ_i is the data uncertainty. Good fits have $\chi^2 \approx 1$, and the deviation from this value denotes the quality of the fit, if the uncertainties are well-understood.

For a given set of density and velocity dispersion values, we find that data points near the center and edge of a system have relatively large uncertainties. As a result, we choose to link model profiles to data profiles at points roughly in the center of the radial range of data. Since some of the models we use are not constrained to have well-defined total masses, we do not use the half-mass radius as the normalizing position. Instead, we force our model profiles to match data profiles at the location where the logarithmic density slope is 2. The logarithmic density slope is defined as,

$$\gamma = -\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}. \tag{3}$$

This parametrizes the shape of a density profile and is particularly useful in describing dual power-law functions like the empirical models. The value $\gamma = 2$ is special because it corresponds to the isothermal density distribution.

Due to their fixed shapes, Plummer and de Vaucouleurs density profiles are straightforwardly fit to the data density profiles by aligning their $\gamma = 2$ locations to that of the data. In order to isolate the best-fit parameters for the generalized NFW and thermodynamic models considered, a nonlinear "amoeba" minimization scheme is implemented. Amoeba minimization searches a multi-dimensional parameter space for non-analytical models — more efficient techniques exist if a model is analytically dependent on parameters (Press et al. 1994). For a given initial parameter guess, a value of χ^2 is calculated and then several other parameter-χ^2 pairs are generated. The amoeba then "oozes" in the direction of the lowest χ^2 value.

It is difficult to uniquely identify the $\gamma = 2$ location for the data density profiles due to noise. We estimate the location using smoothed versions of a system's γ profile, but there are non-negligible uncertainties. As an example of the possible impact of these uncertainties, we have investigated three different Lynden-Bell model fits utilizing different $\gamma = 2$ locations. After estimating the central, "best guess" $\gamma = 2$ position, low and high value estimates are determined as follows: look for the positions where $\gamma = 1.8$ and $\gamma = 2.2$ (10% difference from $\gamma = 2$), take the maximum difference between these positions and the central value as the uncertainty. All three minimizations result in the same best-fit parameter value, but their χ^2 values are 8.3 (high), 3.8 (central), and 1.9 (low). The χ^2 values for the other model fits follow similar patterns. This variation highlights the fact that we are unable to interpret our χ^2 in an absolute sense. We must therefore limit our discussion to relative values for particular choices of $\gamma = 2$ positions.

For several simulations, amoeba minimization generates widely disparate best-fit parameter values for the Lynden-Bell model depending on the initial step size in the search. This result reflects the possibility of the amoeba minimization settling in local minima of parameter space instead of the absolute minimum. To clarify the amoeba behavior, one of my students has written and implemented an alternative method for sampling parameter space. A Markov Chain Monte Carlo (MCMC) minimization locates the region in parameter space wherein the minimum parameter value is located.

When we have applied MCMC minimization to the Lynden-Bell model, 500 random model parameter ν values are generated and associated χ^2 values are subsequently calculated. Each successive ν value is determined in the following manner. Given the preceding χ^2 value, denoted χ^2_{i-1}, the MCMC minimization first calculates a mean new step size, Δ^0_i, in parameter space. The mean new step size is calculated using

$$\Delta^0_i = \Delta \tanh\left(\chi^2_{i-1} - \chi^2_0\right) + 1, \tag{4}$$

where χ^2_0 is a constant that delineates between very large and very small step sizes and Δ is a scale factor. In this manner, mean step sizes will rapidly increase for $\chi^2_{i-1} > \chi^2_0$ and rapidly decrease for $\chi^2_{i-1} < \chi^2_0$. The actual next step size is then randomly drawn according to,

$$\nu(\chi) = \frac{4}{\Delta^0_i \sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{4\left(\chi - \Delta^0_i\right)}{\Delta^0_i}\right)^2\right), \tag{5}$$

where Δ^0_i is determined from Equation 4. We have found that the MCMC minimization reliably locates the region in parameter space containing the absolute best-fit ν value. Performing the MCMC minimization prior to the amoeba minimization of Lynden-Bell and Maxwell-Boltzmann models will ensure that an appropriate initial step size is chosen, resulting in the best-fit parameters for each evolved system.

4. Dissemination

The PI plans to submit the results of this work to The Astrophysical Journal, the pre-eminent peer-reviewed journal for American astrophysics research. Due to the significant impact of student researchers on this project, the PI intends to include at least one student as a co-author. Any student co-authors will share the scientific and editorial workload, giving them valuable experience in dealing with referees, page charges, etc. This submission will complete a series of papers already in publication (Barnes & Williams 2011, 2012). The usual practice for astrophysics work is to also submit research results to an on-line archive managed by the Cornell University Library, arXiv.org. This resource allows researchers around the world to have quick and cost-free access to the lastest work being done by their peers. I choose to post papers on arXiv.org only after the peer-review process, but that is not a requirement.

5. Past Faculty Research Awards

The PI was awarded a Faculty Research Award in the 2006-2007 academic year based on a proposal entitled "Describing Stellar Orbits in Triaxial Galaxy Models". Findings based on work from that award were presented by the PI at the 212th American Astronomical Society meeting and at the 14th Annual Faculty Research Day.

REFERENCES

Ahmed, Z., Akerib, D. S., Arrenberg, S., Attisha, M. J., Bailey, C. N., Baudis, L., Bauer, D. A., Beaty, J., Brink, P. L., Bruch, T., and 48 coauthors 2009, Physical Review Letters, 102, 1301

Barnes, E. I., Sellwood, J. A., Kosowsky, A. 2004, The Astronomical Journal, 128, 2724

Barnes, E. I., Williams, L. L. R. 2011, The Astrophysical Journal, 728, 136

Barnes, E. I., Williams, L. L. R. 2012, The Astrophysical Journal, 748, 144

Binney, J., Tremaine, S. 1987, Galactic Dynamics, Princeton University Press, Princeton, N.J.

Clowe, D., Bradac, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., Zaritsky, D. 2006, The Astrophysical Journal, 648, L109

de Blok, W. J. G., McGaugh, S. S., Bosma, A., Rubin, V. C. 2001, The Astrophysical Journal, 552, L23

Faber, S. M., Gallagher, J. S., 1979, Annual Review of Astronomy and Astrophysics, 17

Governato, F., Brook, C., Mayer, L., Brooks, A., Rhee, G., Wadsley, J., Jonsson, P., Willman, B., Stinson, G., Quinn, T., Madau, P. 2010, Nature, 463, 203

Lithwick, Y., Dalal, N. 2011, The Astrophysical Journal, 734, 100

Lynden-Bell, D., 1967, Monthly Notices of the Royal Astronomical Society, 136, 101

Moore, B., Quinn, T., Governato, F., Stadel, J., Lake, G., 1999, Monthly Notices of the Royal Astronomical Society, 310, 1147

Navarro, J. F., Frenk, C. S., White, S. D. M. 1996, The Astrophysical Journal, 462, 563

Navarro, J. F., Frenk, C. S., White, S. D. M. 1997, The Astrophysical Journal, 490, 493

Navarro, J. F., Hayashi, E., Power, C., Jenkins, A. R., Frenk, C. S., White, S. D. M., Springel, V., Stadel, J., Quinn, T. R. 2004, Monthly Notices of the Royal Astronomical Society, 349, 1039

Nitadori, K., Aarseth, S. 2012, Monthly Notices of the Royal Astronomical Society, 424, 545

Plastino, A. R., Plastino, A. 1993, Physics Letters A, 174, 384

Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P. 1994, Numerical Recipes, Cambridge Univ. Press: New York, NY

Rubin, V. C., Ford, W. K. 1970, The Astrophysical Journal, 159, 379

Salpeter, E.E. 1955, ApJ, 121, 161

Springel, V. 2005, Monthly Notices of the Royal Astronomical Society, 364, 1105

Taylor, J. E., Navarro, J. F. 2001, The Astrophysical Journal, 563, 483

Tsallis, C. 1988, Journal of Statistical Physics, 52, 479

van Albada, T. S. 1982, Monthly Notices of the Royal Astronomical Society, 201, 939

Zwicky, F. 1937, The Astrophysical Journal, 86, 217

Testing Thermodynamic Models of Dark Matter Halos

Eric I. Barnes, Department of Physics

VITAE SUMMARY

Professional Preparation

Northeast Missouri State University	Physics	B.S. 1995
Louisiana State University	Physics	Ph.D. 2001
Rutgers University	Astrophysics	Post-doctoral Researcher 2001-2004
University of Minnesota	Astrophysics	Post-doctoral Researcher 2004-2006

Appointments

Associate Professor, Department of Physics, University of Wisconsin—La Crosse, 2010 - present

Assistant Professor, Department of Physics, University of Wisconsin—La Crosse, 2006 - 2010

Closely Related Publications

1. "Entropy Production in Collisionless Systems. II. Arbitrary Phase-Space Occupation Numbers."
   Barnes, E.I., Williams, L.L.R. 2012, ApJ, 748, 144
2. "Entropy Production in Collisionless Systems. I. Large Phase-Space Occupation Numbers."
   Barnes, E.I., Williams, L.L.R. 2011, ApJ, 728, 136
3. "The Radial Orbit Instability in Collisionless N-Body Simulations."
   Barnes, E.I., Lanzel, P.A., Williams, L.L.R. 2009, ApJ, 704, 372
4. "Velocity Distributions from Nonextensive Thermodynamics."
   Barnes, E.I., Williams, L.L.R., Babul, A., & Dalcanton, J.J. 2007, ApJ, 655, 847
5. "Density Profiles of Collisionless Equilibria. II. Anisotropic Spherical Systems."
   Barnes, E.I., Williams, L.L.R., Babul, A., & Dalcanton, J.J. 2007, ApJ, 654, 814
6. "Density Profiles of Collisionless Equilibria. I. Spherical Isotropic Systems."
   Barnes, E.I., Williams, L.L.R., Babul, A., & Dalcanton, J.J. 2006, ApJ, 643, 797
7. "Scalelengths in Dark Matter Halos."
   Barnes, E.I., Williams, L.L.R., Babul, A., & Dalcanton, J.J. 2005, ApJ, 634, 775
8. "Semi-analytical Dark Matter Halos and the Jeans Equation."
   Austin, C., Williams, L.L.R., Barnes, E.I., Babul, A., & Dalcanton, J.J. 2005, ApJ, 634, 756

GRANT PROGRAM Faculty Research Grant	REFER TO RFP FOR ALLOWABLE CATEGORIES **FOR UW-L GRANTS OFFICE USE ONLY**			
PROPOSAL TITLE **Testing Thermodynamic Models of Dark Matter Ha**	PROPOSAL NO.	Total Funds Proposed		Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Eric I. Barnes	Fiscal Year			

A. PI/PD and Co-PIs (List each separately with title)	First Name	M	Last Name	Title	Funds Requested By Proposer		Funds Granted
1.	Eric	I	Barnes	Associate Pr	$5,000		
2.							
3.							
4.							
5.							
6.							
OTHER PERSONNEL	First Name	M	Last Name	Title			
1.							
2.							
3.							
4.							
TOTAL PI/PD and Co-PIs (1-6) and Other Personnel (1-4)					$5,000		

B. REPLACEMENT COSTS (contact dean's office for current per credit amount)			
1. (0) Credits	$0		
C. STUDENT WORKERS (SHOW NUMBERS IN BRACKETS)			
1. (0) RESEARCH/GRADUATE STUDENTS	$0		
2. (1) UNDERGRADUATE STUDENTS			
TOTAL STUDENT WORKERS	$0		
TOTAL SALARIES AND WAGES (A+B+C)	$5,000		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000)			
1			
2	$0		
3	$0		
TOTAL EQUIPMENT	$0		
E. TRAVEL			
1 DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)			
2 INTERNATIONAL	$0		
TOTAL TRAVEL	$0		
F. OTHER COSTS			
1. MATERIALS, EQUIPMENT LESS THAN $1,000, AND SUPPLIES			
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION	$0		
3. SERVICES - EXTERNAL	$0		
4. SERVICES - INTERNAL	$0		
5. OTHER	$0		
TOTAL OTHER COSTS	$0		
G. TOTAL COSTS (A THROUGH F)	$5,000		
H. FUNDS FROM OTHER SOURCES TO SUPPORT THIS PROJECT			
1	$0		
I. AMOUNT OF THIS REQUEST (G) OR (G MINUS H)	$5,000		

Note: Budget justification / narrative must be submitted with this budget sheet.

Testing Thermodynamic Models of Dark Matter Halos

Eric I. Barnes, Department of Physics

BUDGET NARRATIVE

1. Faculty Stipend

The PI is requesting one month of summer salary support, $5000.

2. Summary

There are no other costs associated with this proposal. The total request is $5000.